A HIGH POWER SOLID STATE CIRCUIT BREAKER FOR MILITARY HYBRID ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

Military vehicle electrical power systems require quickly responding fault protection to prevent mission failure, vehicle damage, or personnel injury. The electromechanical contactors commonly used for HEV protection have slow response and limited cycle life, factors which could result in fuse activation and disabling of the vehicle, presenting a dangerous situation for the soldier. A protection technology not often considered is Solid State Circuit Breakers (SSCB), which have fast response and good reliability. Challenges of extremely high currents and voltages, high temperatures, and harsh conditions have prevented SSCBs from being effective in high power military vehicle electrical systems. Development of an SSCB for military vehicle power systems would increase electrical power system capacity and expand mission capability. The development of a 1.2 kV/200A Silicon-Carbide MOSFET based SSCB for combat HEVs is presented. The key innovation is packaging that minimizes losses, allows high temperature operation, and simplifies cooling requirements. We present results that show response times of less than 5 μs, operational ambient temperatures higher than 125°C, and a current density of 0.4 A/cm^3. Our next-generation design will achieve a much greater current density of 12 A/cm^3 by accommodating up to 2,000 A in a 10 in^3 package. We present a compelling case that SSCBs overcome electromechanical contactor limitations while providing additional capacity and mission capability.

INTRODUCTION

Expanded mission needs have increased the required electrical power system capacity for land, air, and sea vehicles. In particular, advanced military Hybrid Electric Vehicles (HEVs) such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV) have increased system voltages and currents beyond the capability of traditional electromechanical protection means [1 – 4]. Since potential fault current magnitudes have become very large, the most pressing need is for an extremely fast switch to prevent damage to subsystem components. Traditional electro-mechanical protective relays are quite slow, and can only typically respond within 10 – 40 ms. Expected lifetime is also a problem for relays, due to the arcing that tends to destroy the contacts. Furthermore, the maximum permissible breaking current reduces by an order of magnitude as the voltage increases from 300 V to 600 V. For example, the EV-500 has an expected lifetime of 150 cycles when breaking 600 A at 300 V, but at 600 V the expected lifetime is only 10 cycles.

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14. ABSTRACT

Military vehicle electrical power systems require quickly responding fault protection to prevent mission failure, vehicle damage, or personnel injury. The electromechanical contactors commonly used for HEV protection have slow response and limited cycle life, factors which could result in fuse activation and disabling of the vehicle, presenting a dangerous situation for the soldier. A protection technology not often considered is Solid State Circuit Breakers (SSCB), which have fast response and good reliability. Challenges of extremely high currents and voltages, high temperatures, and harsh conditions have prevented SSCBs from being effective in high power military vehicle electrical systems. Development of an SSCB for military vehicle power systems would increase electrical power system capacity and expand mission capability. The development of a 1.2 kV/200A Silicon-Carbide MOSFET based SSCB for combat HEVs is presented. The key innovation is packaging that minimizes losses, allows high temperature operation, and simplifies cooling requirements. We present results that show response times of less than 5 μs, operational ambient temperatures higher than 125?C, and a current density of 0.4 A/cm3. Our next-generation design will achieve a much greater current density of 12 A/cm3 by accommodating up to 2,000 A in a 10 in3 package. We present a compelling case that SSCBs overcome electromechanical contactor limitations while providing additional capacity and mission capability.

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Silicon MOSFETs, SiC MOSFETs, and IGBTs are all worth considering with regard to extremely fast, high voltage, and high current switching devices [5 – 8]. MOSFETs have the lowest static loss as long as the R_{DS} is minimized. This is an advantage over IGBTs for minimizing the steady-state conduction loss, since the IGBT static losses become quite large at high currents and voltages. MOSFETs naturally parallel well, so on-state loss can be reduced with size and cost tradeoffs. Silicon MOSFETs with adequate voltage and current ratings are currently available from several manufacturers. However, the primary disadvantages of the silicon MOSFET are: (1) large R_{dson} and thus high losses at high system voltages, and (2) limited operating temperatures. Advantages of SiC MOSFETs include higher operating temperature, higher operating voltage, and lower R_{dson} at high voltages which substantially reduces power dissipation and thus cooling requirements.

Our overall objective is to aid the move toward higher capacity electric power systems by developing a solid-state circuit breaker (SSCB) which outperforms electromechanical relays. We achieve this objective by developing a device which accommodates high voltages, high currents, and high operating temperatures; operates very quickly (μs); is programmable and scalable; and is similar in size, weight, and cost to existing electromechanical relays.

TYPICAL POWER SYSTEM NEEDS

Figure 1 shows a simplified model of a vehicle electric power system which was developed to determine protective device requirements [1, 2]. Fuses and electromagnetic relays are typically used to protect the electrical power system, and for next-generation power systems which are capable of extremely high normal operating and abnormal fault currents, these devices simply cannot respond fast enough to protect the vehicle electrical systems. In a worst case scenario, an unprotected fault might result in the battery pack and thus the entire vehicle becoming disabled due to damage or fuse activation.
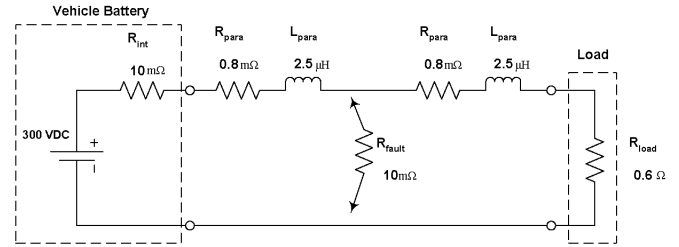
Figure 1. Typical vehicle electrical power system model

In this model, the nominal 300 VDC battery voltage normally supplies 500 A continuous current to a 0.6 Ω load at the time of fault. Vehicle wiring is also included, represented by the parasitic resistance and inductance of the cabling. A low impedance fault is applied midway between equivalent resistances and inductances. Figure 2 shows the battery fault current which results. Prior to the fault occurring, the battery provides 500 A to the load. When the fault occurs, the load impedance reduces to the series combination of battery internal impedance, parasitic resistance and inductance, and the fault resistance. The time constant is very small—in this case just 120 μs. Since the initial rate of rise of fault current is dependent on the V/L ratio, the initial di/dt can reach very high levels very quickly. In this case the initial di/dt is 100 A/μs, and the fault current can reach magnitudes of several thousand amps within less than 100 μs. The situation is substantially worse for a fault near the battery pack, where the inductance could be much lower. The steady-state fault current, if left unprotected, could reach 15 kA.
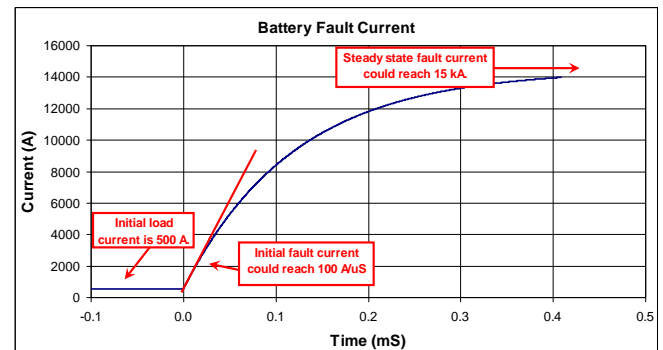
Figure 2. Electrical system model response to a fault. The fault occurs at t = 0 s.

Typical combat vehicles have two types of battery protection—fuses and electromagnetic relays. The slow response of electromagnetic relays is important when considering that if the relay does not respond quickly, the fuse may activate to isolate the fault. This is problematic since the fuse cannot be reset like the electromagnetic relay once the fault clears. Fuses in general are relatively slow, and are a function of the I^2t rating of the fuse. In certain fault scenarios, if the electromagnetic relay does not respond quickly enough, the fuses will activate first, disabling a portion of the vehicle, or in the case of an HEV, the entire vehicle. A more serious condition will occur if vehicle wiring damage occurs before either the relay or fuse activate. Consequently, it is vital to provide a resettable protective device that provides fast protection in high voltage, high current, and high temperature environments.

COMPARISON OF SWITCH TECHNOLOGIES

We first compared SiC MOSFET, Si IGBT, and Si MOSFET switches to determine the optimal device technology for the SSCB. We evaluated performance metrics such as voltage, current, temperature, response time, reliability, cost, size, and availability. The three dominant metrics in these device comparisons are: (1) the power dissipation of the switch while the SSCB is closed and actively carrying load current, (2) the speed with which current can be interrupted in the event of a fault, and (3) maximum junction operating temperature.

Given the requirement for an operating bus voltage of $300 - 600$ VDC, and a current rating of $500–2,000$ A, IGBTs exhibiting a forward voltage drop of up to $4–5$ VDC at static load current would require appreciable thermal management of up to $5,000$ W continuous dissipation incurred when carrying normal load current. More significant is that this forward voltage drop and the attendant dissipation cannot be appreciably reduced by paralleling IGBTs irrespective of the number of devices in parallel. Also, bidirectional current flow is not permissible in IGBTs and can only be achieved with the addition of an anti-parallel diode or a topology of back-to-back IGBTs, the latter of which incurs increased voltage drop under load conditions. As a result of these shortcomings, IGBTs are not a competitive candidate for high-power SSCB applications.

Silicon MOSFETs overcome some of these limitations, and they present the advantages of rapid switching and reduced losses by paralleling multiple devices. However, the Si MOSFET suffers from greatly increased drain-source/on-state resistance (and consequently losses) as the operating voltage and temperature requirements increase. This is particularly important for the HEV SSCB application, where ambient temperatures could exceed $100°C$ and bus voltages of up to 600 VDC are desirable.

The SiC MOSFET advantages include its low on-state losses when compared to the other devices, exceptionally rapid switching speed, $1,200$ V blocking voltage, and high operating junction temperature. Device operation is guaranteed to at least $150°C$, and future generation devices may operate as high as $300°C$. The high operating junction temperature of the SiC device, combined with the ability to reduce MOSFET switch on-state resistance to a minimal level by paralleling devices, permits the reduction of on-state losses and simplifies thermal management in high ambient temperature environments such as combat HEVs. Another advantage of the MOSFET device compared with the IGBT is the inherent bidirectional ohmic conduction characteristic of the switch. This feature permits reverse current flow in the presence of regenerative or charging current flow without additional gating of the power switching device. Based on these device comparisons, we focused primarily on the SiC MOSFET device for development of the SSCB.

SYSTEM DESCRIPTION

SSCB Design

Figure 3 shows a block diagram of the SSCB electronic control circuitry. The SSCB incorporates circuitry to operate the SiC switch and to provide intrinsic hardware protective functions using both load current and voltage sensing to determine the presence of fault conditions. The control circuitry is triggered by either a 24 V or 12 V input as would be similarly required to actuate a mechanical contactor. The power contacts of the SiC SSCB power busses serve as the two switch terminals of a conventional contactor. In this way, the SSCB could be a drop-in replacement for the protective relay. At power-up, the breaker is normally open

and must be closed by a remote logic input. Once the command is initiated to open the SSCB to isolate a fault, breaker opening is latched and can be reset to reclose the breaker via remote logic input. SSCB state and health status is conveyed to the On-Board Vehicle Power (OBVP) management system via a separate logic status signal.

A photograph of the completed SSCB is shown in Figure 4. This SSCB provides 1.2 kV, 200 A, and 5 μs response time capability in a 35 in^3 package weighing 1.8 lbs. (0.4 A/cm^3). Our design for the next generation package achieves greater current density by accommodating up to 2,000 A in a 10 in^3 package (12 A/cm^3).
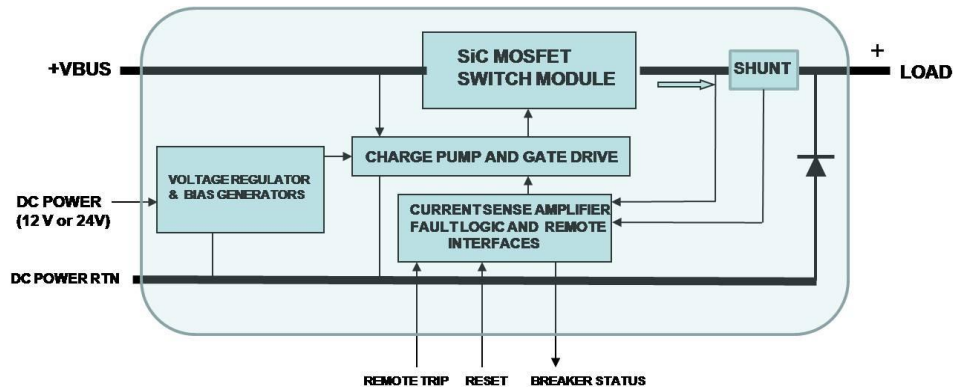
**Figure 3.** Schematic of the SSCB electronic control circuitry
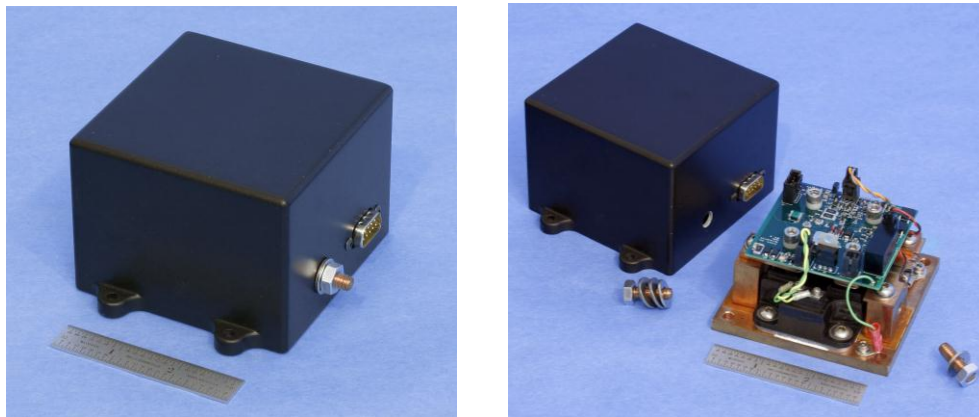
Figure 4. Solid state circuit breaker. Ratings are 1,200 V, 200 A, and 5 μs response time. Size is 3.6 x 3.6 x 2.7 in., and weight is 1.8 lbs.

A High Power Solid State Circuit Breaker for Military Hybrid Electric Vehicle Applications

Multi-Chip Module Design

The core of the SSCB is a Multi-Chip Module (MCM) which achieves high power density and optimal thermal management. The MCM is mounted to a heat spreader and mounting baseplate for optimal heat transfer, and an electronic PCB resides on top of the MCM to provide control functions. Terminal blocks provide high current field connection points for the source and load connections, while a low current connector provides inputs for DC power and auxiliary remote signals. The MCM package permits efficient heat transfer to the mounting surface via the heat spreader baseplate, which presents low thermal resistance from the MCM's heat transfer surface at the bottom of the module. In applications where convective cooling is required, the heat spreader baseplate can be mounted to a finned heat sink.

The MCM was fabricated in compliance with MIL-PRF-38534E, for both military and space applications. MOSFET and diode die and chip resistors were used to create a small, efficient package with low parasitics and good thermal properties.

The MCM circuit design takes advantage of the fact that SiC MOSFETs naturally parallel very well. Figure 5 shows the schematic diagram for our MCM module, and Figure 6 shows the completed MCM. The MCM consists of two switches each having five parallel SiC MOSFETs, and wherein each MOSFET incorporates a gate drive resistor and an anti-parallel SiC Schottky diode. The module connections feature high current terminal connections and gate drive inputs with a MOSFET source Kelvin connection to separate gate drive current from the main load current path. The two composite switches in the module may be paralleled to form a single ten parallel-MOSFET switch with a nominal 8 milli-ohm on-state resistance and 200 A capability. Alternatively, the two individual switches also permit series-connected half bridge applications with simple external wiring connections and 100 A rating.
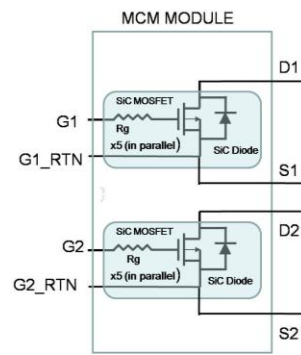
**Figure 5.** Internal circuitry for the MCM

**Figure 6.** Photograph of the completed SiC MCM

TEST RESULTS

Functional Tests

Figures 7 through 9 show the characteristics of the fully integrated SiC MCM SSCB in several fault scenarios and in normal remotely commanded opening and closing operations. Figure 7 shows the soft start feature, where the switch closes softly into a 104 A load. The soft start interval in this case has been set to roughly 10 mS. Figure 8 shows a remotely commanded trip event, where the 100 A load is isolated from the source within 5 µs. Figure 9 shows a long duration slowly increasing load current culminating in an overcurrent trip event when the load current reaches 125% of rated load current (125 A). Figure 10 shows that after the SSCB detects a fault and opens, it can also be repeatedly reclosed remotely to attempt to restore the loads. In this case, since the fault still remains, the SSCB experiences a sequence of three reclosure attempts and is then locked out due to the fault persistence.
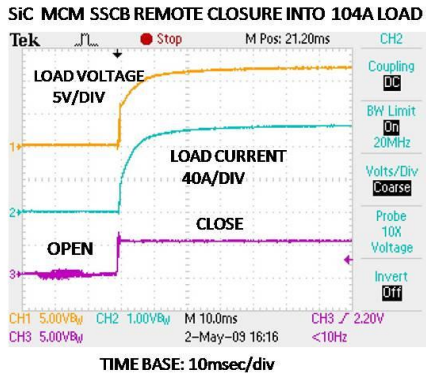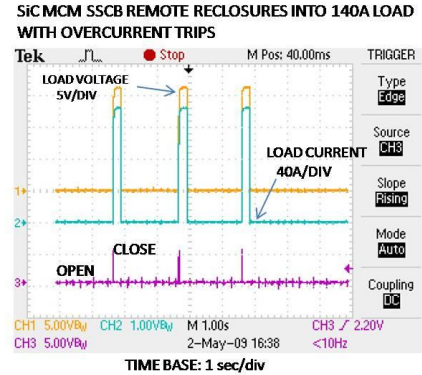
Figure 7. SiC MCM breaker remote "soft start" closure into a 104 A load
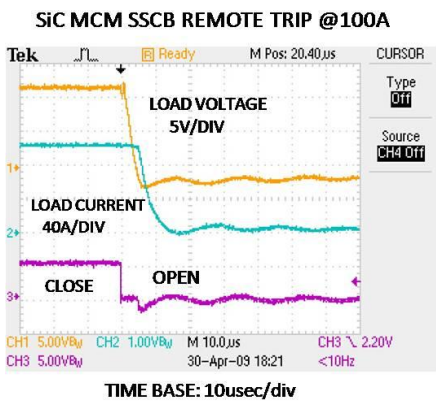
Figure 8. SiC MCM breaker remote trip isolating the source from a 100 A load
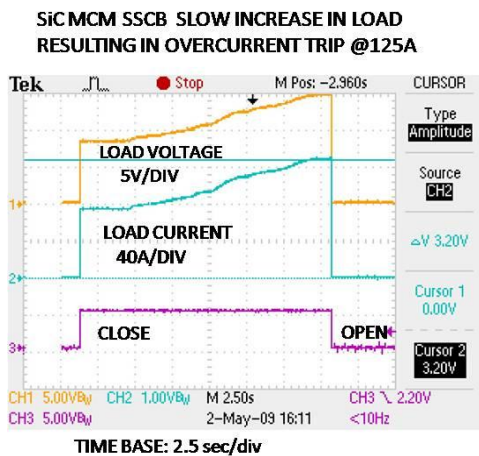
Figure 9. SiC MCM breaker closure followed by a long duration slow increase in load current leading to a 125 A overcurrent trip

Figure 10. The SSCB executes three consecutive remote reclosures into a 140 A load, each resulting in an overcurrent trip since the fault threshold is 125 A.

Note that load voltage and current fall times in breaker opening actions are on the order of 5 μs. The control circuitry is also able to distinguish between short duration non-persistent overcurrents (e.g., load inrush), long duration overcurrents, and overcurrent in the presence of rapid voltage collapse. The latter event causes immediate breaker opening, and the former events result in delayed opening similar to an inverse time breaker characteristic.

## MCM On-State Resistance and Switch Power Dissipation

The thermal impedance from each SiC MOSFET to the baseplate of the MCM package is roughly 1.1°C/W. At 100 A, with ten SiC devices paralleled in the MCM, this creates an 11°C rise of junction temperature over the case temperature. At 200 A, since the power dissipation increases four times, a 44°C rise of junction temperature over the baseplate temperature occurs. Data from Cree on the behavior of the SiC device's R_{dson} versus temperature characteristic indicate a definite minimum at a junction temperature of 100°C. This suggests that operation at 100°C junction temperature in a given design is optimal and would minimize losses at a specified power level. However, operation to a junction temperature of 200°C is possible, so baseplate temperatures of up to 156°C with currents of 200 A can be

accommodated. The R_{dson} of the SiC switch is also a strong function of V_{GS} drive level. Data from Cree suggests that a 33% lower R_{dson} is achievable by driving V_{GS} at 20 V as compared with R_{dson} with 15 V gate drive. We can provide gate drive of up to 22 V in our SSCB to further minimize losses. For example, the SiC MCM switch R_{dson} would be 9.5 milli-ohms with $V_{GS} = 20$ V versus an R_{dson} of 12.5 milli-ohms with $V_{GS} = 15$ V. These data obtained from Cree were supported by data obtained during our production testing of the MCM module.

To evaluate high temperature performance, we operated the MCM up to 200°C and compared R_{dson} measurements to manufacturer data. The results in Figure 11 show good agreement between our results and manufacturer data. Further, while published data is only available to 150°C, we demonstrated that the MCM could operate well at temperatures up to 200°C.

MCM Bidirectional Current Flow

Bidirectional current flow is inherent in a MOSFET when driven into the ohmic region by sufficient gate-source potential. In applications of the SSCB wherein regeneration can occur and current is returned to the battery from the vehicle motion, the SSCB can readily accommodate reverse power flow without additional gating action. This would be typical of HEVs in which energy recovery to the battery upon braking is a normal function. In the SSCB we have designed all circuitry to support bidirectional functionality.
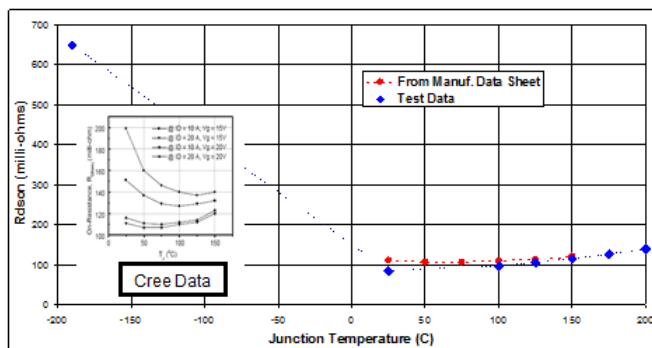
Figure 11. SiC MOSFET operational data compares well to manufacturer data between 20–150°C, and the MCM can operate to 200°C.

CONCLUSIONS

In this paper we presented the development of a high power, 1.2 kV/200A Silicon-Carbide MOSFET SSCB for military vehicle electrical power systems. We designed, fabricated, and evaluated an SiC-based SSCB prototype which incorporates a creative packaging scheme to support high voltage, high current, high operating temperature environments, while minimizing power losses. The key innovation is packaging that minimizes losses, allows high temperature operation, and simplifies cooling requirements. We present results that show response times of less than 5 μs, operational ambient temperatures higher than 125°C, and a current density of 0.4 A/cm^3. Our next-generation design will achieve a much greater current density of 12 A/cm^3 by accommodating up to 2,000 A in a 10 in^3 package. We present a compelling case that SSCBs overcome electro-mechanical contactor limitations while providing additional benefits, and can be produced at comparable size, weight, and cost.

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DISCLAIMER

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